

Computer Simulation of a Direct Sequence Spread Spectrum Cellular Radio Architecture

Chia-Chi Huang

Abstract—This paper describes a computer simulation study to evaluate the channel capacity of a direct sequence spread spectrum cellular radio architecture which is based on code division. The cellular radio architecture utilizes the processing gain provided by a wide-band multipath RAKE receiver to suppress multicell/multiuser interference. As a result, the same piece of radio spectrum can be reused in every cell. We use a step-by-step approach to verify the basic idea behind the spread spectrum cellular radio architecture. Computer simulations are used to calculate the distributions of signal-to-reference ratio (SIR). From SIR distributions, we can easily calculate the channel capacity of the cellular radio architecture. Technical requirements to fulfill potential system performance are also discussed. Finally, an 800 MHz system example is given for cellular mobile radio telephone application.

I. INTRODUCTION

IN traditional cellular radio system design, much emphasis has been put on narrow-band systems for voice communications [1], [2], [19], [20]. In these narrow-band systems, a whole service area is divided into cell-based clusters, and frequency spectrum is reused spatially in different clusters. Frequency reuse is achieved by assuring sufficient propagation attenuation from a cell to other cells using the same frequency band.

Within a cluster, the radio spectrum is divided into channel sets and the channel sets are further divided and used by each cell in the cluster [3], i.e., the separation of radio signal from a cell to another cell is achieved by frequency division.

In order to increase the efficiency of spectrum usage (measured in terms of number of voice channels/MHz $\times$ unit area) in a cellular radio telephone environment, two approaches can be taken:

- 1) reducing cell size;
- 2) increasing cochannel protection capability.

Reducing cell size has the effect of increasing available spectrum per unit area. Microcellular concepts were motivated by this observation. On the other hand, increasing cochannel protection capability has the effect of reducing the number of cells in a cluster, i.e., increasing amount of spectrum which can be allocated to each cell. For example, directional antennas can be used in cellular mobile telephone environments to achieve this goal [4].

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Recently, a direct sequence spread spectrum with code division multiple access scheme was proposed by Qualcomm, Inc. as a method to achieve much higher spectrum efficiency in cellular mobile radio telephone application [11]. This system uses the interference suppressing capability of code division multiple access (CDMA) to claim a many fold increase in channel capacity over analog AMPS system [12] and even over newly developed digital TDMA system [13]. In order to understand the operation principle and the limitation of a CDMA-based cellular radio architecture, we conceptually designed a similar system and evaluated its channel capacity by computer simulation. The system we considered differs from Qualcomm's system in two major aspects.

- 1) Our system does not execute downlink (from base to mobile) power control. Every base transmits at the same power level in all code channels.
- 2) Ideal RAKE receivers are assumed to be used in our system.

In Section II, we describe the difference between narrow-band transmission and wide-band transmission in a multipath propagation environment. This section serves as background for understanding the importance of spread spectrum wide-band transmission and multipath reception in the cellular system design. In Section III, we describe our direct sequence spread spectrum cellular radio architecture in detail and verify its operation from the simplest two-cell single-channel case (Section III-A), more complicated multiple-cell single-channel case (Section III-B), to the more general multiple-cell multiple-channel case (Section III-C).

A system example for 800 MHz cellular mobile radio telephone application is given in Section IV to demonstrate our cellular design concept. Practical considerations in implementing the cellular system are discussed in Section V. A summary is presented in Section VI.

II. NARROW-BAND AND WIDE-BAND TRANSMISSION

Multipath propagation occurs in either mobile radio or indoor radio communications. In these radio communication environments, a transmitted signal might undergo several reflections and local scatterings on a variety of paths before reaching a receiver. The received signals traveling via different paths suffer random time delays, amplitude fluctuations, and carrier phase shifts. We call this phenomenon "multipath fading."

In order to describe this multipath fading channel, a mathematical model was proposed by Turin in his 1956 paper [5]. In

his paper, the multipath channel is modeled as a linear filter. Suppose $\text{Re}\{\sigma(t)e^{j\omega_0 t}\}$ is transmitted and $\text{Re}\{\rho(t)e^{j\omega_0 t}\}$ is received (ω_0 is the carrier frequency), Turin proposed the following relation:

$$\rho(t) = \sum_{k=0}^{\infty} a_k \sigma(t - t_k) e^{j\theta_k} + v(t) \quad (1)$$

where $\sigma(t)$ is complex-valued lowpass representation of the transmitted signal. $v(t)$ is additive complex Gaussian noise and $\{a_k\}$, $\{t_k\}$, $\{\theta_k\}$ are the path strength, path delay, and carrier phase shift respectively, of the various transmission paths. In the following discussions, the combined effects of antennas and filters used in the transmitter and receiver chain have also been lumped into the expression of (1), besides the effect of the radio propagation channel itself. For a fixed set of transmitter and receiver positions, we call the 3-tuples $\{a_k, t_k, \theta_k\}$ the multipath profile at the particular receiving point. From (1) we model a multipath channel between a fixed set of transmitter and receiver pair in the equivalent baseband with the following impulse response:

$$h(t) = \sum_{k=0}^{\infty} a_k \delta(t - t_k) e^{j\theta_k}. \quad (2)$$

In (2), $\delta(\cdot)$ is the Dirac delta function and we have neglected the noise term in (1). If we take the Fourier transform of both sides, we get frequency response in the equivalent baseband as

$$H(\omega) = \sum_{k=0}^{\infty} a_k e^{j(\omega t_k + \theta_k)}. \quad (3)$$

Until now we have ignored the fact that the 3-tuples $\{a_k, t_k, \theta_k\}$ are function of receiving locations, assuming a fixed transmitter location. The maximum value of t_k in (2) at which a path can be received by a radio receiver while it is moving around is called the maximum delay spread, Δ . For example, in urban areas a typical Δ is 5–10 μs (6). If the transmission bandwidth is much smaller than $1/\Delta$, i.e., $\ll 100$ kHz, then the factors $e^{j\omega t_k}$ in (3) are all approximately unity over the band (6). As a result, we have the following equivalent baseband relation by vector summation:

$$H(\omega) = \sum_{k=0}^{\infty} a_k e^{j\theta_k} = A e^{j\Phi}. \quad (4)$$

This is the flat fading (Rayleigh or Rician) situation encountered in narrow-band transmission. Every frequency component within the transmission bandwidth suffers the same amount of amplitude fluctuation and phase shift. As a receiver changes its position, both A and Φ will also change because multipath profiles change. From both mathematical modeling and narrow-band propagation measurements, we know a received signal tends to fade about every half a wavelength and the fade depth sometimes reaches several tens of decibels [10].

If the bandwidth of the transmitted signal is much larger than $1/\Delta$, we have the case of wide-band transmission [7]. In this case, a diversity effect can be achieved in the frequency domain because not all the frequency components of the

transmitted signal tend to fade together [14]. Equivalently in the time domain, different transmission paths can be resolved if both spread spectrum signaling and a matched filter receiver are used. The various transmission paths produce a diversity effect because not all of them tend to fade together [9]. As a result, the combined power of various paths does not change as dramatically as in the narrow-band case.

III. SPREAD SPECTRUM CELLULAR ARCHITECTURE

Here we consider a spread spectrum cellular radio architecture in which the whole service area is divided into cells and each cell is served by a base. A mobile communicates with another mobile or the landline network through a base. The base directly serving a mobile is called the mobile's "home base." We call the transmission from a mobile to its home base the "uplink" transmission and the transmission from a home base to its associated mobile the "downlink" transmission. In the following, by "received signal power level" we mean the combined power of various received signal paths. As spread spectrum code division is considered here, by a "channel" we mean either an uplink code channel or a downlink code channel. We use the term "mobile" to mean either a mobile radio in a car or a portable radio carried by people.

The following is a list of assumptions from which we depart to establish a direct sequence spread spectrum cellular architecture.

- 1) Our system performance is limited by interference coming from users using other code channels within the same frequency band.
- 2) Our spread spectrum signaling bandwidth is large enough such that under most channel conditions we have wide-band transmission, i.e., the diversity effect of multiple transmission paths can be utilized.
- 3) Our receiver has a RAKE structure which utilizes multipath diversity in the data detection process and measures combined power of various received signal paths.
- 4) Our information data signaling rate is low enough such that intersymbol interference can be neglected.
- 5) The number of pseudo-noise (PN) codes available for code division multiplexing is large enough to support potential applications.
- 6) Uplink transmission and downlink transmission have to be separated either in frequency or in time. Here, we assume that they are separated in frequency.
- 7) Different code channels in either uplink or downlink transmission use different PN code sequences.
- 8) Every base transmits at the same power level in its downlink code channels. A specific PN code sequence is used as an identification code for each base.
- 9) Every mobile transmits at a power level such that its home base always receives at the same power level, i.e., power control is executed in uplink transmissions.
- 10) The uplink channel and downlink channel are reciprocal from propagation loss point of view.
- 11) A mobile always chooses its home base to be the one that provides the largest received signal power level in its identification code channel.

- 12) A system gain, G , provided by our RAKE receiver through spread spectrum code division is large enough such that the wanted signal can be detected with large probability, e.g., probability ≥ 0.99 .

Now we want to show that under the assumptions described above a spread spectrum cellular radio system can be established. Our discussion will be centered on the calculation of SIR and its distributions. Here, we use a step-by-step approach to verify our points, starting from the simplest two-cell and single-channel case. More complicated cases will be discussed afterward.

A. Two Cells and Single Channel Situation

Suppose we have two adjacent cells with base A and base B, as shown in Fig. 1. Each cell has a single uplink and a single downlink channel. A single user is associated with each cell and conducts continuous transmission and reception. Let user X choose A as its home base and user Y chooses B as its home base. Due to symmetry we look only at uplink SIR at base A and downlink SIR at user X. Here we define P_{AX} to be the power level X receives from base A. Analogous definitions are used for P_{BX} , P_{AY} , P_{BY} , etc. According to assumption 11), we know

$$P_{AX} \geq P_{BX}. \quad (5)$$

Equation (5) says downlink SIR is always larger than 0 dB.

Now we turn to the uplink case. Due to assumption 11), the following is also true:

$$P_{BY} \geq P_{AY}. \quad (6)$$

By propagation loss reciprocity, we have

$$P_{YB} \geq P_{YA} \quad (7)$$

From assumption 9), we get

$$P_{XA} = P_{YB} \quad (8)$$

Therefore, from (7) and (8), we have

$$P_{XA} \geq P_{YA}. \quad (9)$$

Equation (9) says uplink SIR is always larger than 0 dB.

This simple example provides us with the insight that SIR can be controlled under the assumptions we made above. The next question to ask is how SIR performs in the more complicated multiple cells and single channel situation.

B. Multiple Cells and Single Channel Situation

Now we consider a case in which there are more than two cells in the cellular system. However, we still assume that every cell has only a single uplink and a single downlink channel. A single user is associated with each cell and conducts continuous transmission and reception.

Here we use computer simulation instead of mathematical analysis to calculate SIR. In our simulation, we use a traditional propagation loss model [15]. This model describes received signal power variation at a fixed radial distance to

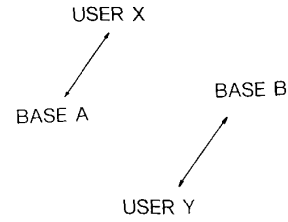


Fig. 1. Two cells and single channel case.

a transmitter by a propagation loss exponent and a lognormal distribution with a certain standard deviation. Propagation loss exponent is the exponent to which radial distance is raised in an inverse power law. Lognormal distribution is used to model shadow fading. It has been found in [15] that the difference in SIR statistics is small between square and hexagonal cells. Therefore, we assume all the cells are square shaped in our simulation due to its simplicity. We also assume that power loss exponent is 4, and standard deviation of log-normal fading is 6, 8, and 10 dB, respectively.

Fig. 2 shows the simulated cumulative distribution of downlink SIR when the whole system consists of 121 cells. In the simulation, we assume the bases are located at the 121 grid points of a uniform-grid structure. A candidate mobile is randomly located within the central cell (square shaped) and the received signal power level from each base is calculated according to the mentioned propagation loss model. The base associated with the largest received signal power level is regarded as the home base and the signals from all the other bases are regarded as interference. Our simulation showed very consistent results for four different sample sizes (2500, 5000, 7500, 10000), and Fig. 2 shows only the results when the sample size is 10000. In order to examine the distribution curves more closely, we expand the initial portion of curves in Fig. 2 in Fig. 3. From Fig. 3 we observe that downlink SIR is better than -4.8 , -5.6 , and -6.0 dB for more than 99 percent of the simulated cases when standard deviation of lognormal fading is 6, 8, and 10 dB respectively.

The simulation of uplink SIR is trickier than the downlink case. Here, we first generate a table of size $48 \times 10\,000$ from the downlink simulation. During each run of downlink simulation we found a home base for a candidate mobile randomly located in the central cell. Each row of the table was then generated such that it consists of normalized interference power received at the mobile from 48 bases (construct a square grid) around the home base. By normalization we mean the dividing of the received power from each surrounding base by the power received from the home base. As a result, each item in the table is less than or equal to one.

The table can be interpreted as a sample space of normalized interference from each of the 48 surrounding bases to a user associated with the home base. Due to power level reciprocity the table can also be interpreted as a sample space of normalized interference from a user associated with the home base to its 48 surrounding bases when uplink power control is in effect. This interpretation makes the table useful for uplink SIR simulation using the Monte Carlo method.

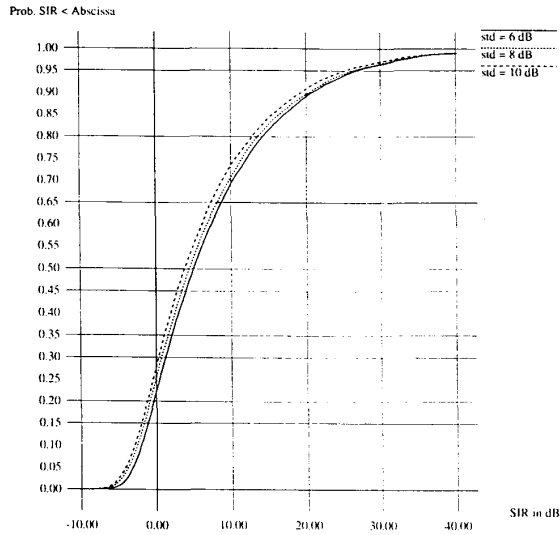


Fig. 2. Simulated distribution of downlink SIR, multiple cell and single channel case.

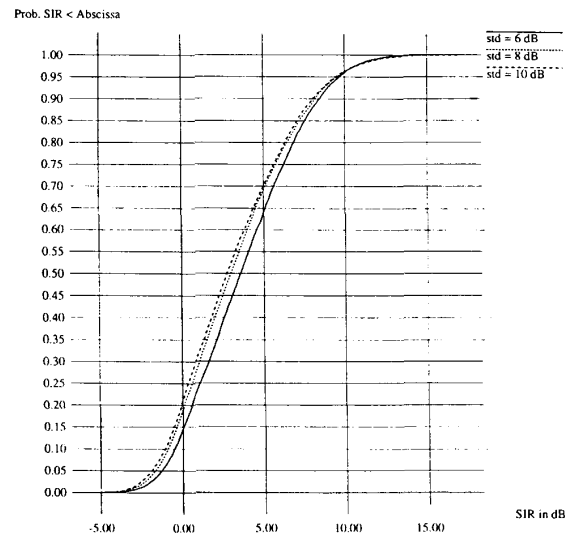


Fig. 4. Simulated distribution of uplink SIR, multiple cell and single channel case.

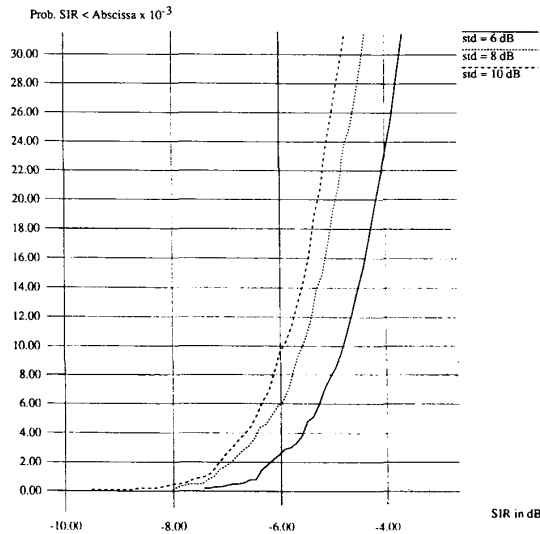


Fig. 3. Initial portion of Figure 2.

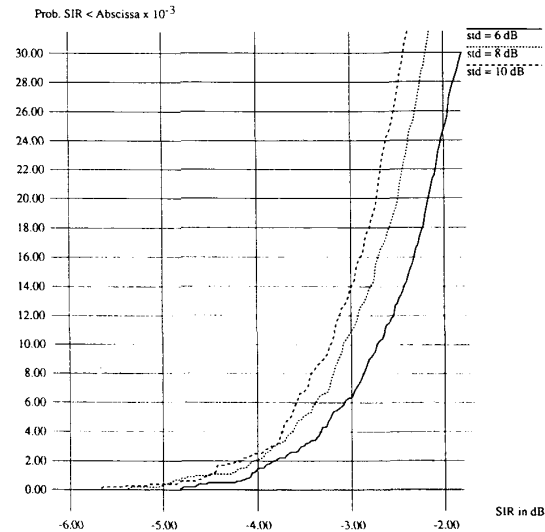


Fig. 5. Initial portion of Figure 4.

Fig. 4 shows the simulated cumulative distribution of uplink SIR under the assumption that a candidate home base is located at the center of a square-grid of 49 bases and each base has a mobile in communication with it. The wanted signal comes from the mobile associated with the central home base and the interference comes from all other mobiles associated with surrounding bases. Our simulation also showed very consistent results for four different sample sizes (2500, 5000, 7500, 10 000), and Fig. 4 shows only the results when sample size is 10 000. Fig. 5 expands the initial portion of the distribution curves in Fig. 4. From Fig. 5 we see that uplink SIR is better than -2.7 , -3.1 , and -3.2 dB for more than 99% of the simulated cases when standard deviation of lognormal fading is 6, 8, and 10 dB, respectively. The simulation results indicate that uplink SIR is better than the downlink case.

C. Multiple Cells and Multiple Channels Situation

Now, we consider the multiple cell situation in which there are more than one uplink and downlink channels in each cell, and each channel is used by a user for continuous transmission or reception. Here, we first divide interference into two different categories, category I counts for interference coming from inside a cell and category II counts for interference coming from outside a cell. For convenience, we assume a wanted signal always has a power of 1.

As discussed before, each code channel uses a different pseudo noise code sequence. In both uplink and downlink cases, N simultaneous users in a cell will have category I interference power of $N-1$. For category II interference cal-

culation in the downlink case, we have to use the results of our simulation, Fig. 3. Another way to look at Fig. 3 says that for the single channel case downlink normalized interference level will be less than 3, 3.6, and 4 for more than 99% of the cases when the standard deviation of lognormal fading is 6, 8, and 10 dB, respectively. Therefore, for N simultaneous users in each cell, category II downlink interference will be less than $3N$, $3.6N$, and $4N$ for more than 99% of the cases when the standard deviation lognormal fading is 6, 8, and 10 dB, respectively. This result is valid because a home base transmits at the same power level in all the code channels.

From the above, we can approximate total interference power in the downlink case, I_D , as following:

$$\begin{aligned} I_D &= 4N & \text{for } \text{std} = 6 \text{ dB} \\ I_D &= 4.6N & \text{for } \text{std} = 8 \text{ dB} \\ I_D &= 5N & \text{for } \text{std} = 10 \text{ dB} \end{aligned} \quad (10)$$

where std is the standard deviation of log-normal fading and N is the number of simultaneous users (code channels).

For evaluating category II interference in the uplink case, we use the same simulation methodology as in the single channel case to simulate multiple channel SIR. Fig. 6 shows our simulation results for channel number equal to 1, 2, 4, 8, 16, 32, 64, and 128, when standard deviation of log-normal fading being equal to 6 (right one in each set), 8 (middle one), and 10 dB (left one), respectively. Fig. 7 shows only the initial portion of cumulative distribution of signal to interference ratio. Fig. 8 shows the relationship between normalized interference level and number of channels under the condition that interference will be less than the plotted line for more than 99% of the cases. From Fig. 8 we know that category II uplink interference under multiple channel situation is well bounded by N , the number of code channels when N is large (say $N > 10$). Therefore, the following equation can be used to calculate total interference in the uplink case, I_v , with a good confidence margin.

$$I_v = 2N \quad \text{for } \text{std} = 6, 8, 10 \text{ dB}. \quad (11)$$

Using (10) and (11), we can calculate interference power in both downlink and uplink cases. A cellular structure can be constructed if a stable and sufficient system gain can be achieved such that interference can be suppressed with large probability, e.g., probability ≥ 0.99 .

From (10) and (11) we observe that downlink interference I_D is higher than uplink interference I_v . This difference comes from the fact that power control is executed only in the uplink case. In this paper we do not consider power control in the downlink case, and suggest it as a future research topic.

IV. A SYSTEM EXAMPLE

In this section, we present an 800 MHz spread spectrum cellular radio telephone system example. The goal of this example is to clarify our cellular design concept rather than to pursue design details.

As mentioned in the beginning, directional antennas can be used at a base to reduce interferences. When M (a small

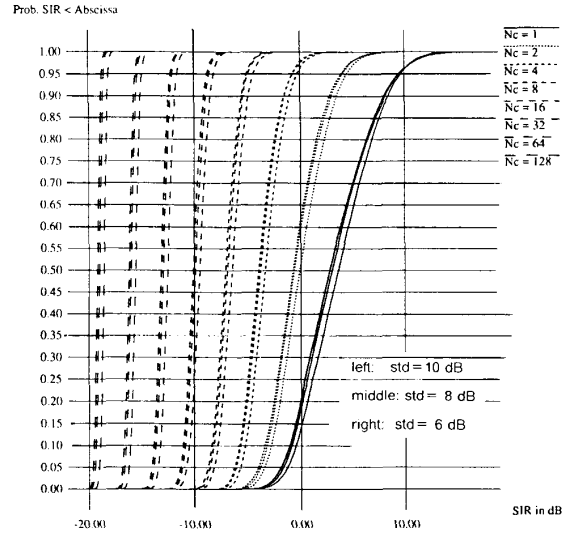


Fig. 6. Simulated distribution of category II uplink SIR, multiple cell and multiple channel case.

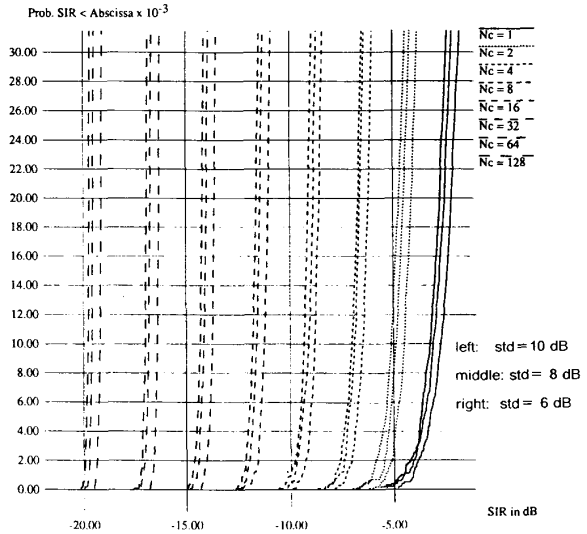


Fig. 7. Initial portion of Figure 6.

integer) directional antennas are used at a base to illuminate M different sectors in a cell, both categories I and II interference can be reduced by a factor of M . This direct effect on interference reduction is possible because at a base, antennas can be erected to a considerable height in an urban/suburban mobile radio environment. Another clue for interference reduction comes from the relatively low speech activity factor, which is about 40% during two-way conversations [16]. The low activity factor of speech signal effects total interference level in a code division multiplexed cellular system directly. Current mobile radio speech/channel coding techniques require about 12 kbit/s data rate and can tolerate channel error rate up to 1% [17]. Without channel coding, a speech coder can perform well at a rate of 8 kbit/s with channel error rate up to 0.1%

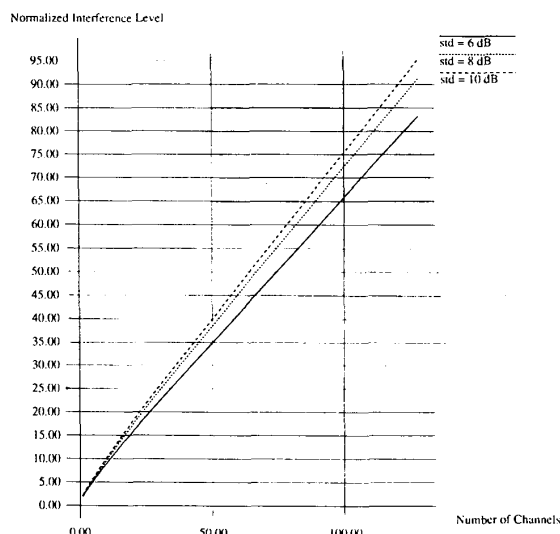


Fig. 8. 99 percentile category II normalized interference level as a function of the number of channels.

[17]. In the following, for illustration purposes, we make the following assumptions:

- a speech coder can function well at a rate of 10 kbit/s with channel error rate up to 0.1%;
- maximum delay spread, Δ , is larger than 1 μ s and less than 10 μ s most of the time;
- four antennas are used in a base and each antenna illuminates a 90° sector;
- voice activity factor is 40%;
- the propagation loss exponent of the radio channel is 4 and the standard deviation of log-normal fading is 10 dB.

At 10 kbit/s baseband signaling rate, the effect of intersymbol interference can be neglected. According to the discussions in Section II, wide-band transmission needs to have a bandwidth larger than 10 MHz (say 10 times $1/\Delta$).

Assuming four directional antennas at a base and a voice activity factor of 40%, we can calculate effective interference power, I_E , in both downlink and uplink cases from (10) and (11) as follows;

$$\begin{aligned} I_E &= 0.5N \quad \text{for downlink case} \\ I_E &= 0.2N \quad \text{for uplink case} \end{aligned} \quad (12)$$

where N is the number of code channels. Due to the unbalance in interference power in the two cases as shown in (12), we have to use different processing gains for downlink and uplink in order to accommodate the same number of code channels in the two cases.

In order to detect a signal correctly with a bit error rate better than 10^{-3} , signal to noise ratio has to be above 7 dB (about 5 in linear scale) if an ideal RAKE receiver is used—see Appendix. Under this detection requirement, we found that a processing gain of 2800 for downlink and a processing gain of 1200 for uplink accommodate more than 1100 code channels in both cases. At a transmission efficiency of 1 chip/Hz, the overall radio spectrum requirement is 40 MHz.

The 40 MHz bandwidth will provide only 500 voice channels per cell in both uplink and downlink cases using the current U.S. narrowband digital cellular architecture, assuming a four-cell cluster structure and 30 kHz transmission bandwidth for 3 TDMA voice channel (21). Based on the calculations done in (21), Qualcomm's system will provide 1920 voice channels per cell within the same total bandwidth. Therefore, our code division based cellular architecture provides more than twice of voice channel capacity than the U.S. digital cellular system. Its performance is not as good as Qualcomm's system because downlink power control is not executed in our system architecture.

V. PRACTICAL CONSIDERATIONS

Programmable matched filters and RAKE receivers have to be used in the spread spectrum cellular radio system. Programmable matched filters are needed because a mobile needs to constantly monitor the received power level from its surrounding bases and needs to be able to change codes when it changes its home base. RAKE receivers are needed because they are most effective in utilizing multipath diversity. A non-ideal RAKE receiver will have lower sensitivity and lower system gain ([7] investigated the performance of various RAKE-like multipath receivers). The lower system gain will directly affect the capacity of the cellular system. References in [8] and [9] present excellent discussions on how a wide-band multipath RAKE receiver can be constructed using currently available technology.

Successful commercial use of the direct sequence spread spectrum cellular radio system also depends on the answers to the following questions:

- 1) how well and cheap can a programmable matched filter and a RAKE receiver be made?
- 2) how many PN codes can be used?
- 3) how well does propagation loss reciprocity hold in two different frequency bands?

It has been shown in [18] that a time-bandwidth product of 2000 and a system gain from 18 to 61 dB can be achieved using a combination of SAW convolver and RAKE demodulator. We believe our system concept is both technically feasible and cost effective, as technology improves and user demand increases. The second question is less a problem when spreading ratio is very large (e.g., >1000). In this case, we probably can use computer generated random binary codes for different code channels. The third question can be answered only by conducting wide-band radio propagation measurements in urban/suburban areas. If this reciprocity does not hold, we can still implement the cellular system by separating uplink and downlink transmissions in time instead of in frequency.

VI. SUMMARY

This paper describes a computer simulation approach in evaluating the channel capacity of an idealized direct sequence spread spectrum cellular radio architecture, which is based on code division. The cellular architecture utilizes the processing gain provided by a wide-band multipath RAKE receiver

to suppress multicell/multiuser interference. The simulation methodology is general and provides an alternative way to evaluate other similar systems.

A step-by-step approach is used to verify the basic idea behind the spread spectrum cellular radio system design. Computer simulations are used to calculate SIR distributions in both downlink and uplink cases. From SIR distributions, we can easily calculate the channel capacity of the cellular radio architecture. Practical considerations in implementing the cellular architecture are also discussed. An 800 MHz system example is given to demonstrate the potential improvement in channel capacity for mobile radio telephone application.

VII. APPENDIX

Suppose a multipath channel provide N paths (resolvable peaks) after a matched filter and each path has amplitude strength of x_i , then an ideal RAKE receiver tries to use a linearly weighted sum of x_i 's for detection in an optimum way. From Schwartz inequality, we know

$$|A \cdot X|^2 \leq |A|^2 \cdot |X|^2 \quad (13)$$

where A is the weight vector and X is the path amplitude vector. The left-hand side of (13) will be equal to its right-hand side if and only if an optimum weight is chosen as follows:

$$a_i = kx_i \quad (14)$$

where a_i is the i th weight element of A and k is constant. Here, we assume k is chosen so that A has a norm of 1. When this optimum weight vector is chosen, we have the following:

$$|A \cdot X|^2 = |X|^2 \quad (15)$$

Equation (15) says the power of weighted sum signal is the same as the power of original signal. The noise power is not changed because A has a norm of 1. As a result, the total power of X can be contributed to data detection, i.e., the performance of an ideal RAKE receiver will be the same as the performance of nonfaded BPSK signaling with the same received signal-to-noise ratio.

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